

# Recent Advances In Multi-Functional Structures

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**Abstract**—The Air Force Research Laboratory (AFRL) and its government and industry partners are actively pursuing a variety of technologies that are revolutionizing the design of future spacecraft structures. Multi-Functional Structures (MFS) is a new design paradigm that seeks to integrate the load carrying capability of traditional structures with other spacecraft functions. The result of this integrated approach is the potential for order of magnitude improvements with respect to mass, cost, and volume. This paper provides an overview of three MFS projects: Lightweight Flexible Solar Array (LFSA), the Advanced Technology Demonstration System (ATDS), and Lithium Battery Core (LibaCore). Both technical and programmatic issues associated with maturing this technology and providing a vehicle for affected technology transition will be presented. Experience has shown that transitioning new technology requires both technical advancement as well as demonstrating benefits that outweigh potential risks. It also requires developing the confidence needed to insert this technology through appropriate ground and flight demonstrations. The primary purpose of this paper is to show how industry and government can partner successfully to achieve these objectives.

program is developing and demonstrating technologies and manufacturing processes that enable a satellite bus to incorporate various spacecraft functions that were previously independent of the structure. Using new technologies, hardware can be miniaturized and either embedded or attached to the bus itself. To make this concept a reality, various satellite functions must be designed with a concurrent engineering approach. In other words, all satellite subsystems must be designed to interact with each other in an integrated fashion, this should be a design priority from the beginning. Satellite functions that can be integrated into a micro configuration include micro-electronics, micro-instrumentation and sensors, power distribution, data handling, flexible circuitry, power generation and storage, structural advances, and even propulsion. This paper will give an overview of the various projects that are on-going at the AFRL's Space Vehicles Directorate. This technology development effort is relatively new and will grow in the years to come. The ultimate goal of the multifunctional structures concept is to demonstrate a fully integrated MFS satellite. At this point, there will be a fine line between what is structure and what is avionics, or batteries, etc.

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## 1. INTRODUCTION

The trend in spacecraft today is to design and manufacture smaller spacecrafts that have the same capabilities or better than their larger predecessors. Smaller spacecraft can drive down launch costs by enabling multiple manifests on board launch vehicles. This capability was previously infeasible, due to the larger spacecraft's mass and volume. The reduction in mass and volume can also allow a spacecraft to be deployed by a smaller launch vehicle class. This can save millions of dollars in launch costs. In addition to making spacecraft smaller, the design must lend itself to mass production. The AFRL Multifunctional Structures

## 2. MULTIFUNCTIONAL STRUCTURE PROJECTS

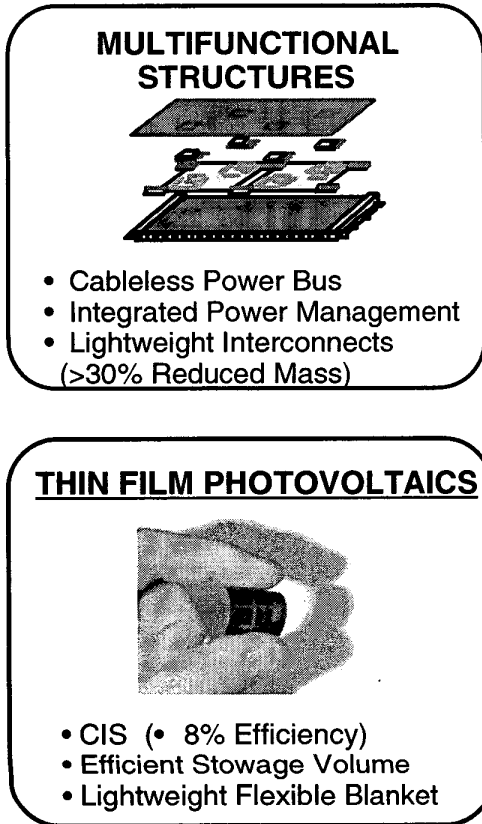
### *Lightweight Flexible Solar Array Flight Project*

Conventional state of practice (SOP) and current state of art (SOA) solar arrays utilize rigid honeycomb substrates to provide the launch stowage and deployed structural support of rigid crystalline Si or GaAs cells. Rigid panel composite facesheet thicknesses (~0.010 inch) and honeycomb densities (1.6 kg/m<sup>3</sup>) have reached the practical producible limits, limiting rigid panel solar array technology to a specific power of ~50 Watts per kilogram (W/kg). A revolutionary solar array approach is required to meet the evolving DoD and NASA specific power (>150W/kg), packaging (300 W/m<sup>2</sup>) and stowage (<0.15 m<sup>3</sup> for 750 W array) requirements. The AFRL, NASA Langley, DARPA and Lockheed Martin are sponsoring an effort with Lockheed Martin that will develop and demonstrate advanced technologies (Figure 1) for solar array applications

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that will result in lower cost, reduced weight, less risk, more reliability, and more available power. Recent advances in shape memory alloy devices, ultralight composites along with thin film Copper-Indium-Diselenide (CIS) photovoltaics have shown the potential of providing solar array systems that produce more than 100 W/kg.



**Figure 1. Advanced Solar Array Technologies**

This program will investigate innovative and efficient solar array deployment schemes that use SMA actuated flexures and mechanisms, thin film CIS photovoltaics, high stiffness, lightweight composite frame structures that can meet the challenging power goal of  $> 150$  W/kg for future NASA and Air Force spacecrafts. The synergistic merging of the SMA and lightweight structures technologies into an advanced lightweight solar array can meet the requirements of the now emerging generation of small satellites. Two flight experiments will demonstrate the key technologies of this program. The first experiment is a two panel solar array that has already successfully flown on NASA's Earth Observation 1 (EO-1) spacecraft of the third New Millennium Program (NMP). The second will be a full size solar array that will fly on NASA's EO-2 spacecraft of the

third NMP technology demonstration flight in 2001. The solar array will be designed, fabricated, and tested by Lockheed Martin. The implementation of this SMA technology toward lightweight solar arrays will result in a significant weight reduction over current satellite systems. The SMA devices will provide a controlled shockless deployment of the solar array, improved testability due to mechanism reset capability, and SMA actuators will eliminate or minimize deployment motors, mechanisms, and part count.

#### *Advanced Technology Demonstration Spacecraft (ATDS)*

On conventional spacecraft, most subsystems such as thermal control, bus structure, and electronics are manufactured and packaged as separate subsystems and are installed on the spacecraft independent of each other in the form of radiators, black boxes to enclose the electronics, and load bearing panels for structural support. These elements are single function elements that are eventually bolted together during final assembly of a spacecraft. Bulky round cables are then used to tie these elements together. Current spacecraft electrical systems involve thousands of feet of cables and numerous connectors to route the power, data transmission, command, control and ground planes around the structure. These conventional systems are extremely heavy and require extensive touch labor to manufacture the spacecraft bus. The objective of integrating electronics onto the spacecraft structure is to substantially reduce the mass and volume that conventional electronics packages have occupied in the past. This includes avionics modules such as Command and Data Handling (C&DH), Electrical Power Systems (EPS), Batteries, etc.

The structures team at AFRL/VS is working with Lockheed Martin Astronautics (LMA) on contract entitled ATDS, that will apply the MFS concept and use multichip modules (MCM) with High Density Interconnect (HDI) packaging to greatly reduce the volume and mass that a conventional avionics package requires (Figure 2). MCM technology involves taking the physical silicon chip die – mounting them on a ceramic substrate with the chip and circuit level interconnections made with metalized traces sputtered onto layers of Kapton. HDI provides the means for a connectorless method for transmitting all of the signals associated with the module to the external world. A method utilizing an "interposer" provides the interface between the ceramic MCM module and a flexible harness. Substantial volumetric savings are obtained with the MCM/HDI combination in that the functionality of the devices is

**Table 1. MFS High Density Interconnect MCM Key Demonstrators**

	<u>FPDM*</u>	<u>Standard Capability</u>	
• SIZE	3.3"X6.6"X0.4"	2 Cards X 8.0" X 9.5" X 1.25"	Std: 6U VME Form Factor
• VOLUME	8.7 in <sup>3</sup>	190 in <sup>3</sup>	> 90% Reduction
• MASS	0.3 Kg	2.2 Kg	> 85% Lower Mass
• POWER	2.5 W	2.5 W	FPDM Incl. Ctrl Circuitry

	<u>IOM**</u>	<u>Standard Capability</u>	
• TOTAL I/O	261	2 Cards X 104 = 208	> 2X I/O Capability
• SIZE	3.3" X 6.6" X 0.4"	2 Cards X 8.0" X 9.5" X 1.25"	6U VME Form Factor
• VOLUME	8.7 in <sup>3</sup>	190 in <sup>3</sup>	> 90% Reduction
• MASS	0.3 Kg	1.0 Kg	70% Lower Mass
• POWER	6.8 W	10 W	> 30% Less Power

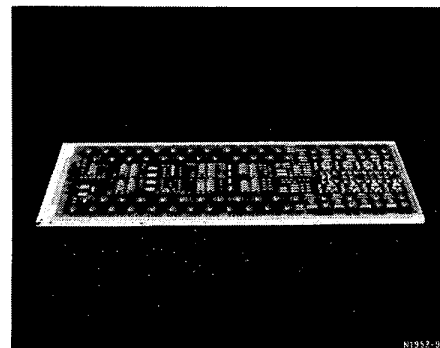
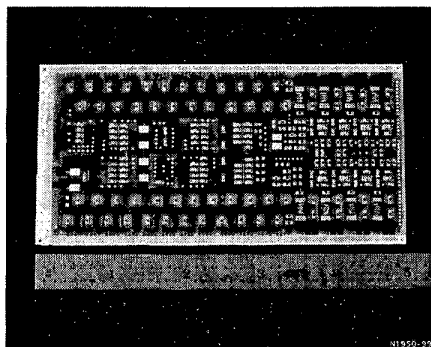
\* Full Power Distribution Module

\*\* Input Output Module

**Table 2. MFS Flexible Circuitry Key Demonstrators**

• VOLUME	> 65% Reduction** over Conventional Round Wire Cables
• MASS	> 85% Reduction** over Conventional Round Wire Cables

\*\* Table 2 Reduction metrics based on STRV study, estimate for overall spacecraft mass savings is 11% based on a similar study on the Stex Spacecraft.



**Figure 2. ATDS Full Power Distribution Module, a Multichip module (MCM), utilizing High Density Interconnect (HDI) packaging format**

obtained without the physical housings typically associated with the devices (as in the case of a standard printed circuit board). The ATDS program is scheduled to conduct vibration, EMI/EMC, and thermal gradient

testing in Feb 00. Previous AFRL MFS programs have successfully integrated and demonstrated the reliability of MCM/HDI electronics and associated interposers, flex circuitry, anisotropic electrical bonding, and thermal

control. Deep Space 1 is one such program in which these technologies were successfully demonstrated as experiments embedded on a spacecraft load bearing structural panel. In fact, the system was successfully reworked in place to correct a minor design error prior to launch. The MFS experiment on DS1 has definitely been a success. DS1 was launched in Oct 99, first data was received in Mar 99. To date, the flight data received correlates almost exactly to the data gathered during panel qualification. Data gathered was primarily MCM electronics functionality, thermal management, and electrical continuity of flex circuitry. Data received from DS1 will continue to be evaluated to determine how performance of the MFS panel is progressing. Another key component of the MFS architecture is flex circuitry, which replaces bulky round wire cables that are normally used on spacecraft. Miniaturizing the electronics and circuitry, and attaching or bonding those subsystems directly to the structure reduces the mass and volume of those subsystems by approximately 85% and 90%, respectively, when compared to conventional spacecraft such as the NRO's STEX. Specifically, STEX's EPS system mass is 2.2kg and volume is 190 in<sup>3</sup>. Compare that to MFS MCM module values of .3kg and 8.7in<sup>3</sup>, respectively (Table 1). These MCM metrics have been demonstrated on the AFRL's Advanced Technology Demonstration Spacecraft (ATDS) project. Reduction of weight and volume will increase the efficiency and performance of spacecraft. It may also allow the spacecraft to be launched on a smaller, less expensive launch vehicle, which would save the mission substantial funds.

To verify that these MFS concepts will work, ATDS will be demonstrated on TechSat21 as critical avionics. ATDS will not be a redundant experiment, it will control the spacecraft and it will be critical that the avionics work because TechSat21 will not have a backup avionics set. The AFRL and LMA are currently working with the TechSat21 program office to establish a manifest strategy. ATDS will provide TechSat21 with a full avionics package, including 6 MCMs, and flex circuitry throughout the length of that spacecraft after deployment, which is 7 meters.

In short, MFS development in the area of HDI MCM development and flex circuitry has just begun to be implemented into spacecraft designs; there are many applications that we have not yet pursued due to limited funding. The AFRL is committed to implementing these concepts as a means to enable micro and nano satellite flight systems.

#### *Lithium Battery Core Development Project*

A next generation battery technology has been developed at AFRL and ITN Energy Systems Inc. recently that truly plays to spacecraft. Yet this solid state battery, Lithium

Battery Core (LiBaCore) has wider applications than space and may eventually be used to add battery pack to the solid state memories, medical device such as pacemaker etc. Benefits include solid state, small volume, and low mass.

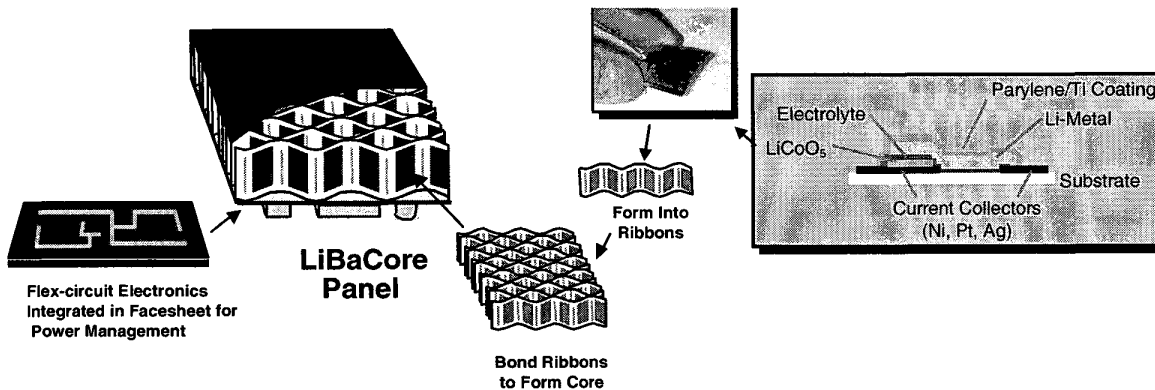
By integrating LiBaCore battery into the honeycomb panel, next generation spacecraft, especially TechSat 21, can minimize mass and package volume, as well as cost, by taking advantage of the following benefits afforded by the multi-functionality of the LiBaCore system.

- **Low Mass:** ITN's solid state lithium battery chemistry results in a cell **specific energy of 200 W-hr/kg** compared to 50 W-hr/kg for conventional wet chemistries. In addition, LiBaCore eliminates the need for battery sleeves, mounting inserts, and the requirement for isothermalization, virtually eliminating mass of support components.
- **Low Volume:** The entire power storage device is packaged within the existing structural envelope.
- **Long Cycle Life at High DOD:** Our lithium battery has repeatably demonstrated high cycle life at 100 percent DOD in a laboratory environment, and will reduce the amount of storage capacity required for a given mission.
- **Safe, Solid-State Design:** LiBaCore is a 100 percent solid-state device, thereby eliminating issues posed by wet chemistries and high battery operating pressures.
- **Versatile Packaging and System Integration/Test:** Traditional spacecraft batteries require strict thermal control, which means mounting on a "cold face" of the spacecraft, requiring pre-launch refrigeration, and testing separately from the rest of the system. Conversely, LiBaCore is a very robust device. It can operate between -50 and 80°C, be mounted almost anywhere on the spacecraft, and does not require special pre-launch handling or testing.

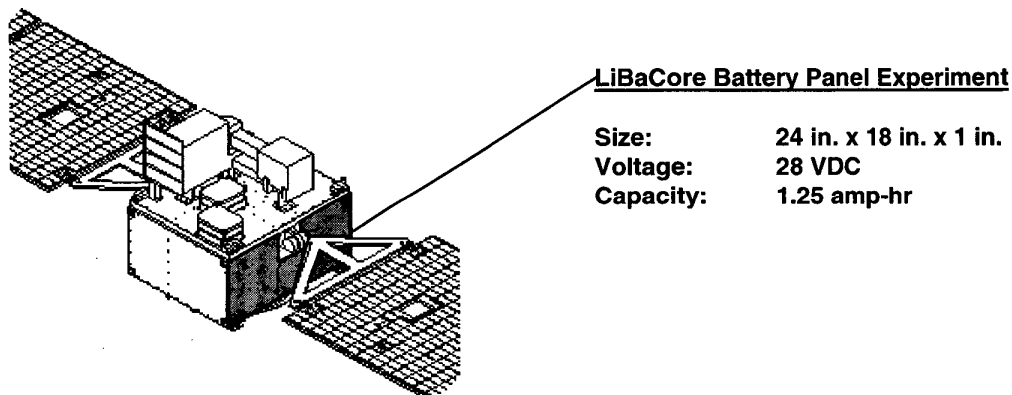
#### LiBaCore Flight Experiment

AFRL/VSDV in cooperation with ITN Energy Systems Inc. proposed the LiBaCore battery panel as a secondary experiment on the MightySat II.2 spacecraft. Unfortunately, the MightySatII.2 program was cancelled. The AFRL and ITN are currently looking for flight demonstration opportunities with various programs, nothing has been finalized yet. Figure 4 shows the manifest configuration proposed for MightySat II.2. One structural panel of the MightySat II.2 bus would have functioned as the battery panel, supplementing the operational spacecraft batteries. Shown are also the preliminary size of characteristics of the proposed

LiBaCore battery panel.



**Figure 3. Revolutionary LiBaCore is a Lightweight, High-Energy Density Battery which Doubles as the Structural Core in a Sandwich Panel.**



**Figure 4. LiBaCore Battery Panel on Potential Flight Spacecraft**

### 3. CONCLUSION

The AFRL will continue in its efforts to make MFS development a reality. The AFRL realizes that MFS is economical in terms of mass and volume savings, which translate directly to lower launch costs and enhanced satellite performance; we also recognize that it is critical for micro and nano satellite development. New MFS concepts are constantly being pursued and the AFRL welcomes ideas from both industry and government organizations in regards to the next development effort.

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**Jim Guerrero** is the Multifunctional Structures program manager within AFRL/VS and resides within the Integrated Structures Team therein.

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